



Advanced Materials and Manufacturing Techniques for Additive Manufacturing of Metal Parts

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Abstract.

The technique of additive manufacturing (AM) has been developed for more than 25 years. By layering and combining materials, additive manufacturing (AM) enables the direct creation of 3D items from CAD models. This innovative method makes it possible to produce previously impossible parts with complex geometries and material compositions. The ability to produce complicated geometries and specialised parts thanks to additive manufacturing, also known as 3D printing, has completely changed the industrial sector. Due to its potential for quick prototyping, decreased waste, and more design freedom, additive printing of metal parts in particular has attracted a lot of attention. This study examines cutting-edge materials and production methods for metal part additive manufacturing. It outlines developing trends and future directions in the area, explores the difficulties and constraints, and gives a summary of the state-of-the-art in metal additive manufacturing at the moment. The impact of several advanced materials utilised in metal additive manufacturing, such as alloys, composites, and functionally graded materials, on the mechanical, thermal, and chemical characteristics of printed parts is also highlighted in the article. Additionally, it explores cutting-edge manufacturing processes including binder jetting, directed energy deposition, and powder bed fusion and clarifies their benefits, drawbacks, and uses. Researchers, engineers, and manufacturers who want to comprehend and take advantage of the developments in materials and manufacturing methods for the additive manufacturing of metal parts can use the research paper as a comprehensive resource.

Keywords : Metal components, advanced materials, manufacturing processes, 3D printing, Graded materials.

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I. Introduction

Rapid prototyping has drawn a lot of attention to additive manufacturing (AM), often known as 3D printing, in recent years. It has increased its capacity to produce a variety of items, such as clothing, jet engines, and turbine blades. Initially, plastics were the most frequently used material in additive manufacturing (AM), but as

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the technology has improved, it is now possible to utilise ceramics, paper, and even polymer matrix composites. Using the Big Area Additive Manufacturing (BAAM) equipment created by Cincinnati INC and Oak Ridge National Laboratory,[1] a Shelby Cobra replica was created using carbon fibre reinforced ABS. By integrating reinforcing materials to increase

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filament strength, this innovation has completely revolutionised composite printing. Composites, which are renowned for having a high specific strength, are widely used in automotive and aerospace applications. However, conventional techniques for producing composites take a long time, need a lot of labour, and are expensive. A qualified [2] worker creating composite materials manually can make mistakes that affect the mechanical qualities of the material. Manufacturers in Western Europe and the USA are increasingly embracing automated composite manufacturing to address these issues and enhance process efficiency.

Three automated [3] composite manufacturing processes—automated tape layup (ATL), automated fibre placement (AFP), and filament winding (FW)—have grown in popularity across a number of industries. [4] Although these methods have been the subject of extensive research, their general application is constrained by the high cost of specialised equipment and the difficulties in producing complicated pieces. However, these approaches are helpful for speeding up production and lowering labour costs because they provide comparable composite strength to conventional manufacturing procedures. By [6] using automated composite tape layers, the aerospace sector, for instance, has achieved a significant decrease in man-hours of between 70 and 85 percent. The [5] use of additive manufacturing is currently expanding significantly in fields including engineering, aerospace, and biomedicine. With the use of this technology, prototyped parts can be produced quickly and affordably without the need for specialised equipment. The comparatively weak bonding in components like green ceramics and low strength of polymers are a disadvantage of additive manufacturing, though. Fillers and fibre reinforcements are utilised to increase strength in order to solve this problem. Fillers have long been used in polymer systems as crack-bridging and toughening agents. For instance, Stratasy Inc. eISSN1303-5150

uses glass whiskers with a diameter of a few millimetres in their speciality filament for printing materials using extrusion. Similar to this, the 3D printing business FiberForge Inc. has created technology that allows carbon fibre filament to be printed on a 6 x 6" build tray [8].

In the past, metal parts were created using subtractive techniques like milling or turning, which include taking material away from a solid block in order to form it into the required shape. However, these techniques can lead to significant material waste, restrictions on the complexity of the designs, and lengthy procedures. These [7] restrictions have been removed with the advent of metal additive manufacturing, which also provides several significant benefits. First and foremost, AM makes it possible to produce extremely detailed and complicated geometries that are either impractical or impossible to produce using traditional manufacturing processes. This creates new opportunities for part lightweighting, design optimisation, and functional integration.

The capacity to create [10] components with superior mechanical qualities is a significant benefit of additive manufacturing for metal parts. The precise control of material composition, microstructure, and mechanical properties is made possible by the layer-by-layer deposition method. Additionally, AM makes it possible to create intricate interior latticework and structures, which can improve the performance and strength-to-weight ratio of metal products.

Due to its distinctive characteristics, additive manufacturing has generated a lot of attention and innovation across numerous industries. Metal additive manufacturing has made it possible to produce lightweight, fuel-efficient aircraft components in the aerospace industry. It has transformed the design of patient-specific implants and prostheses in the medical industry. Metal additive manufacturing has also gained favour in the automotive, energy, and defence industries due to its potential to



enhance part performance, cut costs, and quicken product development.

II. Modern Metal Additive Manufacturing Techniques

1. An overview of metal additive manufacturing techniques currently used

Different processes are included in metal additive manufacturing, each having their own benefits, restrictions, and uses. An overview of some popular methods for metal additive manufacturing is provided below:

a. Powder Bed Fusion (PBF): One of the most popular techniques for metal additive manufacturing is powder bed fusion (PBF). Selective Laser Melting (SLM) and Electron Beam Melting (EBM) are two of its primary

methods. While an electron beam is utilised in place of a laser in SLM, EBM uses a high-energy laser to layer-by-layer melt and fuse metal powder. PBF offers a high degree of accuracy, a decent part density, and the capacity to create intricate shapes. It has uses in the automotive, medical, and aerospace industries [11].

b. Binder Jetting: Binder jetting is the selective layer-by-layer application of a binder to a metal powder bed. After printing the complete component, it goes through a post-processing stage when it is sintered to reach its ultimate density. The advantages of binder jetting include its high throughput, affordability, and capacity to print with a variety of metal materials. It has uses in the tooling, consumer goods, and automotive industries[12].

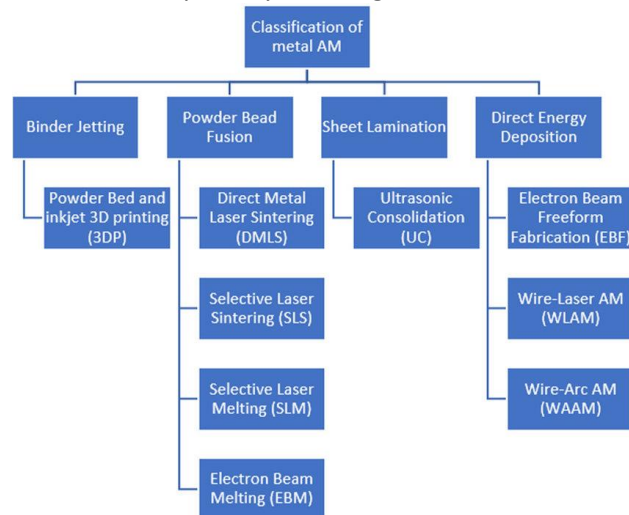


Figure 1: Categorization of additive manufacturing techniques

c. The WAAM (Wire Arc Additive Manufacturing) process: Layer by layer, metal wire material is melted and fused by WAAM using an electric arc. It is an economical method appropriate for producing massive metal objects. WAAM is frequently employed in sectors including shipbuilding, construction, and the manufacture of substantial structural components because it offers high deposition rates [14].

d. DED: Directed Energy Deposition: DED, often referred to as laser metal deposition, entails employing a laser or electron beam to deposit metal powder or wire material on a substrate.

Large-scale parts may be produced using this method, and it also enables the use of coating and repair procedures as well as the blending of various materials. DED is frequently used in the tooling, aerospace, and defence industries and is versatile [15].

e. Thermoplastic Material Extrusion: A thermoplastic filament is fed into an extrusion nozzle or hot end during this operation, usually in the shape of a spool. The nozzle heats the filament to its melting temperature at which time it turns into molten material that may be put onto a build platform layer by layer. To precisely regulate the deposition route, the



extrusion nozzle is positioned on a gantry system that can move in the X, Y, and Z directions. The molten thermoplastic solidifies and connects to the earlier layers as it is extruded, creating a solid item. To achieve good adhesion of the printed portion, the build platform is frequently heated or furnished with a bed adhesion mechanism [16].

2. Discussion of each technology's benefits and drawbacks

a. PBF: Powder Bed Fusion

Benefits: PBF provides outstanding part density, high precision, and the capacity to create complicated shapes. Due to the melted particles' fast solidification after melting and the ensuing strong bonding, it has good mechanical qualities. PBF can be used for a variety of applications because it is appropriate for a wide range of metal materials.

Cons: Post-processing procedures like heat treatment are frequently needed with PBF in order to eliminate residual stresses and get the best possible material characteristics. Due of the requirement for layer-wise melting, it can be relatively sluggish, and PBF machines typically have higher equipment costs than other methods.

b. DED: Directed Energy Deposition

Benefits: DED is appropriate for applications requiring rapid manufacturing and maintenance because it enables the fabrication of massive parts at high deposition rates. It gives flexibility because it can work with various materials and integrate many alloys into a single component. Additionally, DED offers high material utilisation and enables manufacture that is close to net shape.

Drawbacks: It include the possibility of lesser accuracy with DED compared to other methods and the potential need for extra machining or polishing to

improve product surface quality. Remaining stresses may be introduced due to the heat source's high energy input, necessitating post-processing actions. Compared to some other metal AM methods, DED systems are frequently more complicated and expensive.

c. Boundary Jetting

Benefits: Because binder jetting can swiftly deposit and bind layers of metal powder, it delivers great throughput and cost effectiveness. It may be used with a variety of metal materials and is appropriate for mass manufacturing. Binder jetting can produce surfaces with a good surface polish, and the subsequent sintering and binder removal operations sometimes just need a few easy steps.

Drawbacks: Binder jetted parts often have a lower density than those produced using other processes, necessitating post-processing procedures like sintering to produce the necessary material characteristics. Binder jetted items' mechanical strength might be less than completely dense ones made in other ways. Binder jetting may also have lesser precision and dimensional tolerances than some other metal AM processes [9].

d. WAAM: Wire Arc Additive Manufacturing

Benefits: WAAM is renowned for having high deposition rates, which makes it ideal for producing large-scale metal parts quickly. Because it uses wire feedstock, which is often more affordable than metal powders, it is a cost-effective method. WAAM has good material characteristics and can treat a variety of metals, including titanium, steel, and aluminium.

Drawbacks: When compared to other metal AM processes, WAAM might not be as accurate or have as good of a



surface polish. Thermal distortions caused by the arc's heat input may necessitate further machining or post-processing procedures. The method might not be ideal for creating intricate interior geometry.

III. Details of Advanced Materials for Metal Additive Manufacturing

Due to advances in research and development, metal additive manufacturing (AM) now uses a wide variety of innovative materials in addition to more conventional ones like stainless steel and titanium. [19] These materials allow for the manufacturing of parts for specialised applications and offer greater performance and enhanced characteristics. Some significant cutting-edge materials used in metal additive manufacturing include the following:

a. Alloys based on nickel:

Inconel and Hastelloy are two nickel-based alloys that are frequently used in the chemical processing, aerospace, and power generating industries. These alloys have good mechanical qualities, outstanding high-temperature strength, and excellent corrosion resistance. Turbine blades, exhaust systems, and chemical processing machinery are a few examples of demanding applications where they are appropriate since they need to be resistant to harsh environments.

b. Alloys of aluminium:

Due to their low density, good strength-to-weight ratio, and thermal conductivity, aluminium alloys—including AlSi10Mg and Al6061—are extensively employed in a variety of industries. Particularly for lightweight components, they find applications in the aerospace, automotive, and consumer products industries. Aluminium alloys have strong resistance to corrosion and can be treated further to have specific qualities.

c. Aluminium Alloys:

Ti6Al4V (often referred to as Ti-6-4) and TiAl6V4 are two titanium alloys that are frequently used in aerospace, medical, and automotive applications. In the case of medical implants, these alloys have great biocompatibility, high strength, and low density. Because of their exceptional ability to resist corrosion, titanium alloys are frequently utilised to produce parts for high-performance automobiles, prosthetic devices, and aircraft engines.

d. Steels with high strength

High-strength steels have high hardness, wear resistance, and toughness, such as tool steels like H13 and maraging steels like MS1. These steels are frequently used in moulds, tooling, and wear-resistant parts. The fabrication of complex geometries and specialised tooling is made possible by additive manufacturing, which is particularly useful in the tool and die sector.

e. chromium-cobalt alloys

Dental crowns, orthopaedic implants, and other dental and medical applications all make use of cobalt-chromium (Co-Cr) alloys, such as Co-Cr-Mo. Excellent biocompatibility, high strength, and resistance to wear and corrosion are all characteristics of Co-Cr alloys.

Patient-specific implants with complex geometries can be created using metal additive manufacturing, improving fit and functionality.

f. Metals that burn easily:

Refractory metals have high melting points, great mechanical qualities, and outstanding heat and wear resistance. Examples include tungsten, molybdenum, and tantalum. Electronics, aerospace, and defence industries all use these metals. Heat-resistant parts, rocket engine parts, electrical connectors, and high-temperature

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furnace components can all be created using additive manufacturing with refractory metals.

g. Aluminium Alloys:

Bronze and brass are copper alloys that are prized for their superior thermal and electrical conductivity. Heat

exchangers, electrical connectors, and electronic parts all use them. Using metal additive manufacturing (AM) processes, copper alloys may be 3D printed, allowing for the fabrication of intricate copper parts with improved heat transfer properties.

Table 1: Summary of different Material advantages and disadvantages

Material	Advantages	Applications
Nickel-Based Alloys	- Excellent corrosion resistance - High-temperature strength - Good mechanical properties	- Aerospace components - Power generation equipment - Chemical processing applications
Aluminum Alloys	- Low density and lightweight - Good strength-to-weight ratio - High thermal conductivity	- Aerospace structures - Automotive parts - Consumer goods
Titanium Alloys	- High strength - Excellent biocompatibility (for medical applications) - Low density	- Aerospace components - Medical implants - High-performance automotive parts
High-Strength Steels	- Exceptional hardness and wear resistance - Good toughness	- Tooling and molds - Wear-resistant components
Cobalt-Chromium Alloys	- Excellent biocompatibility (for dental and medical applications) - High strength - Corrosion resistance	- Dental and medical implants - Orthopedic implants
Refractory Metals	- High melting points - Excellent mechanical properties - Resistance to heat and wear	- Aerospace components - Defense applications - High-temperature furnace components
Copper Alloys	- Excellent thermal and electrical conductivity	- Heat exchangers - Electrical connectors - Electronic components

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IV. Result and Discussion

1. Testing for Mechanical Tensile:

The INSTRON 5982 mechanical test apparatus, which has a 100 kN force cell, was used to perform the tensile test at room temperature. The experiment was carried out in accordance with the global standard ASTM E8/E8M, [20] titled "Standard Test Methods for Tension

Testing of Metallic Materials." A crosshead speed of 5 mm/min was applied to the test specimens, which came in both cylindrical and dog bone shapes.

The test findings for samples printed in the z-direction as opposed to the x and y directions in the instance of dog bone-shaped samples made using 3D printing demonstrate much greater



resistance values. Furthermore, according to the modulus values, samples produced in the y-

direction are stiffer than those printed in the x and z directions shown in figure 2.

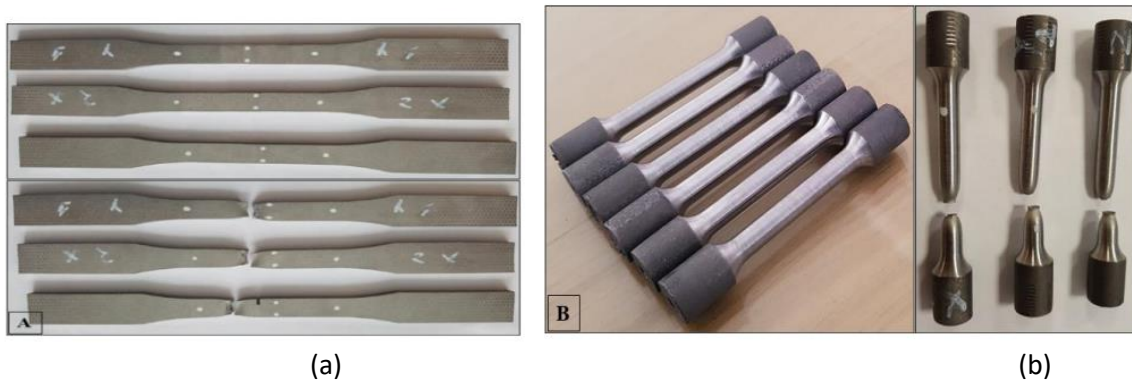


Figure 2: (a) Bone shape material 3D design (b) Cylindrical shape 3D printing material

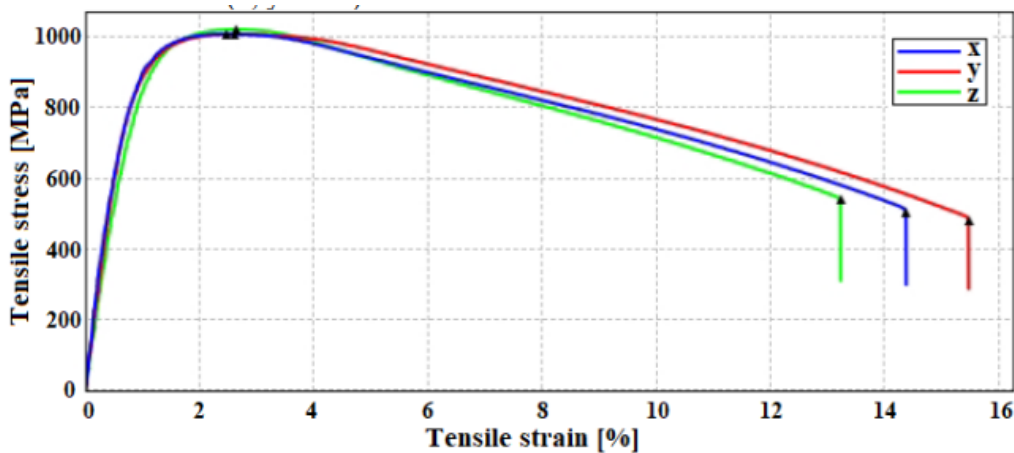


Figure 3: After tensile tests, the stress-strain curves of cylindrical metallic materials manufactured in 3D. These results will be further investigated together with morphostructural investigations, which will provide light on the failure modes seen in the samples in all three printing directions. It will be possible to gain a thorough understanding of the performance and failure characteristics of the printed samples in various orientations by integrating the findings of the mechanical tests with the morphostructural analysis.

2. Structural examination of morphology

Analysing a substance or object's morphology and structure to determine its characteristics is known as morphostructural analysis. Morphostructural analysis is the process of examining the physical and structural characteristics of 3D printed samples in order to learn more about their internal and external features, flaws, and failure processes.

In additive manufacturing, morphostructural analysis entails analysing the morphology and structure of 3D printed materials. The internal

and surface features, flaws, and failure processes of the printed materials are characterised using methods like optical microscopy, scanning electron microscopy (SEM), X-ray computed tomography (CT), X-ray diffraction (XRD), and mechanical testing. These investigations shed light on the microstructural features, such as the existence of defects like voids or cracks, porosity, surface roughness, and grain boundaries. Researchers and engineers can improve the printing process, find flaws or defects, and correlate these findings



with the mechanical performance and failure behaviour of the 3D printed objects by using

morphostructural analysis.

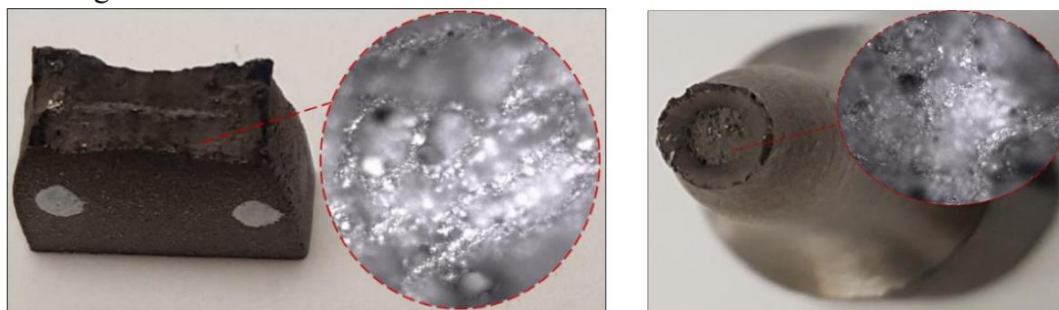


Figure 4: Images captured by optical microscope at the failure region of 3D-printed metal samples

Table 2: Summary of Composite material

Material Test (Standards)	Fiber Content (%)	Orientation to print direction	Modulus (GPa)	Strength (MPa)
FiberGlass - Polyamide 13	28	y-z plane	2.72	42.7
Glass fiber - Polyamide 13	-	-50°C (ASTM E647)	25.3	y-z plane
Carbon Fiber - Polyamide 13	-	Tensile (ASTM D3039)	-	-
Carbon Fiber - Polyamide 13 (surface treatment)	28	Flexural (ISO178-1993(E))	-	-
Carbon Fiber - Polyamide 13 (surface treatment)	44	Flexural (ISO178-1993(E))	-	-
Carbon Fiber - Polyamide 13 (surface treatment)	44	Flexural (ISO178-1993(E))	-	-

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The samples from the laser printing process were subjected to morphostructural investigation using optical microscopy and scanning electron microscopy (SEM). The analysis concentrated on the region of the samples where failure occurred during mechanical tension testing. Images of the cylindrical and dog bone samples were taken using the MEIJI 8520 microscope's 100x magnification video camera for optical microscopy. Figure 4 shows these pictures.

V. Conclusion

Both materials and production methods have advanced significantly in the field of metal additive manufacturing. With a focus on the

benefits and drawbacks of various methods such powder bed fusion, directed energy deposition, and binder jetting, this research study has offered an outline of the state-of-the-art in metal additive manufacturing. The effects of advanced materials, such as alloys, composites, and functionally graded materials, on the mechanical, thermal, and chemical properties of printed metal parts have also been investigated. The use of cutting-edge materials in metal additive manufacturing has produced encouraging results in terms of enhancing the durability, performance, and strength of printed products. Customised alloy compositions have made it possible to



manufacture pieces with particular mechanical characteristics, and composite materials have added improved functions and reinforcing techniques. The tight control of the additive manufacturing process made possible by modern production methods has enhanced the part quality and dimensional accuracy. Providing versatility for various manufacturing needs, powder bed fusion, directed energy deposition, and binder jetting each have their own advantages and uses. There are still a number of issues and restrictions that need to be resolved. Cost, scalability, surface polish, post-processing, and the necessity for additional study on material characterisation and qualification are a few of these concerns. It will be essential to get over these obstacles if additive manufacturing of metal parts is to be widely used in a variety of industries.

VI. Limitation and Future Direction

The future of metal additive manufacturing depends on overcoming current obstacles and pushing the limits of available materials and manufacturing processes. Future research directions and developing trends could go in the following directions:

- Manufacturing that combines different materials and additive manufacturing techniques to produce complex, multifunctional objects with a range of attributes is known as multi-material and hybrid manufacturing.
- In order to achieve real-time process control and quality assurance during additive manufacturing, improved sensing and monitoring systems must be developed.
- In order to guarantee the mechanical, thermal, and chemical performance of metal parts produced using additive manufacturing, it is necessary to better understand the properties of materials and develop standardised testing procedures.
- Scalability and productivity: Creating high-speed additive manufacturing

methods to fulfil industrial demands, such as large-scale printing and parallel printing techniques.

- Recycling and sustainable materials: To reduce waste and advance the circular economy in additive manufacturing, research is being done on recycling and sustainable materials.

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